NASA Glenn Propulsion Systems Lab: Update on Calibration Testing

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2015-06 SAE International Icing Conference

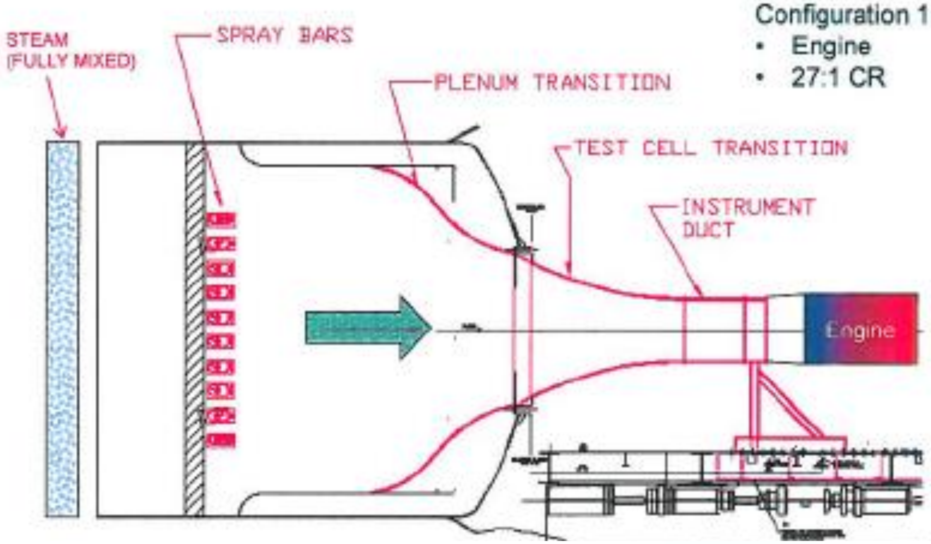
Prague, Czech Republic

Agenda

- PSL Icing Configurations and Capabilities
  - Engine
  - Driven Rig
- Icing/Ice Crystal Cloud Characterization
  - Water Content
  - Particle Size
  - Uniformity
  - Particle Temp

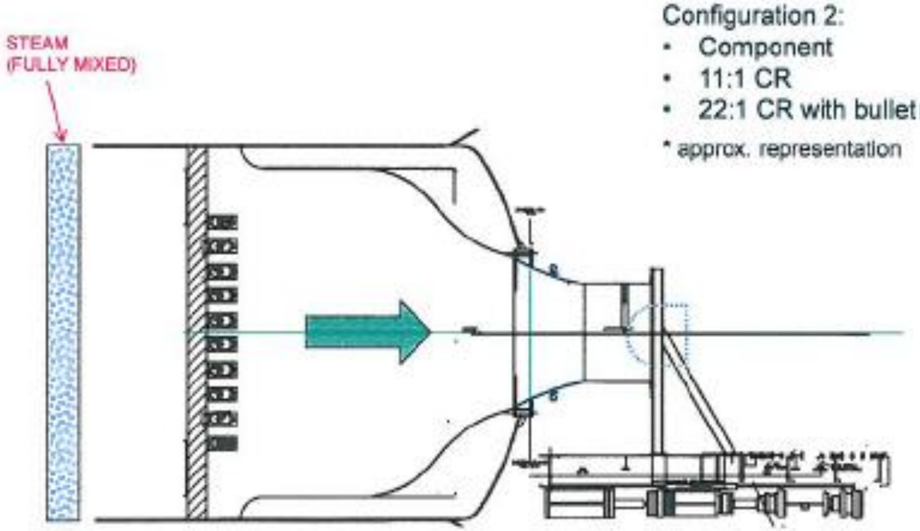
Icing Calibration Configurations

Configuration 1:
- Engine
- 27:1 CR



Configuration 2:
- Component
- 11:1 CR
- 22:1 CR with bulletnose

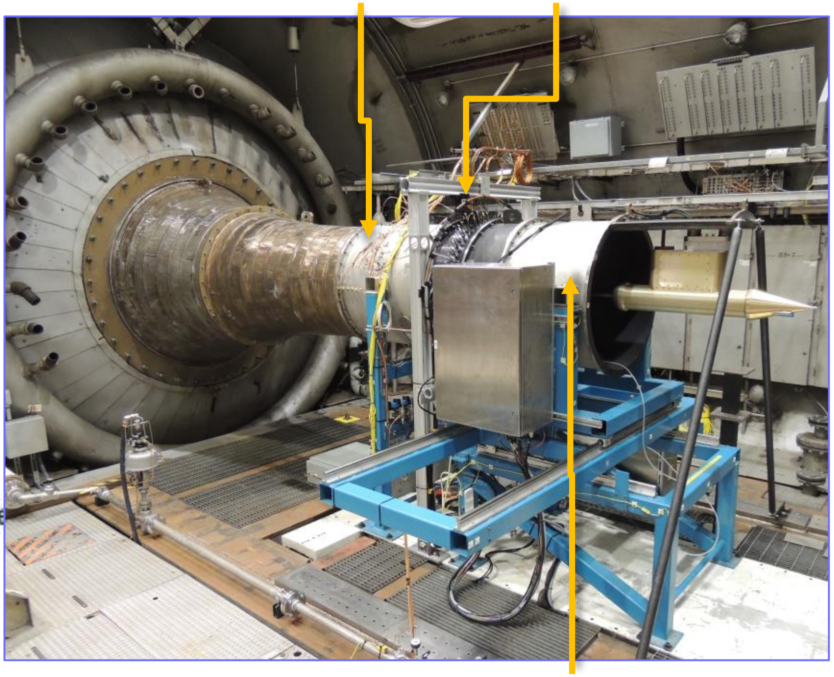
* approx. representation



Modification upstream of spraybars

Aero-Thermal Cal Duct
Pres., Temp., Rel. Humidity

Tomography &
Raman Duct



Cloud Calibration Duct
Water Content, Particle Sizing

PSL Operating Range – Icing System

Specification	Min	Max
Engine / Rig Dia. (in | cm)	24 | 60	72 | 180
Air Flow Rate (lbm/s | kg/s)	10 | 5	330 | 150
Altitude, pressure (kft | km)	4 | 1.2	50 | 15
Total Temp (°F | °C)	-60 | -50	50 | 10
Mach Number	0.15	0.80
TWC (g/m^3)	0.5	8.0 *
MVD (um)	15	>100 #

* Evidence that probe under-measured

Particles larger than ≈ 60 um are NOT fully glaciated.

Setting Conditions in PSL

Given the atmospheric environment (P_{amb}, T_{amb}, Mach) of concern,

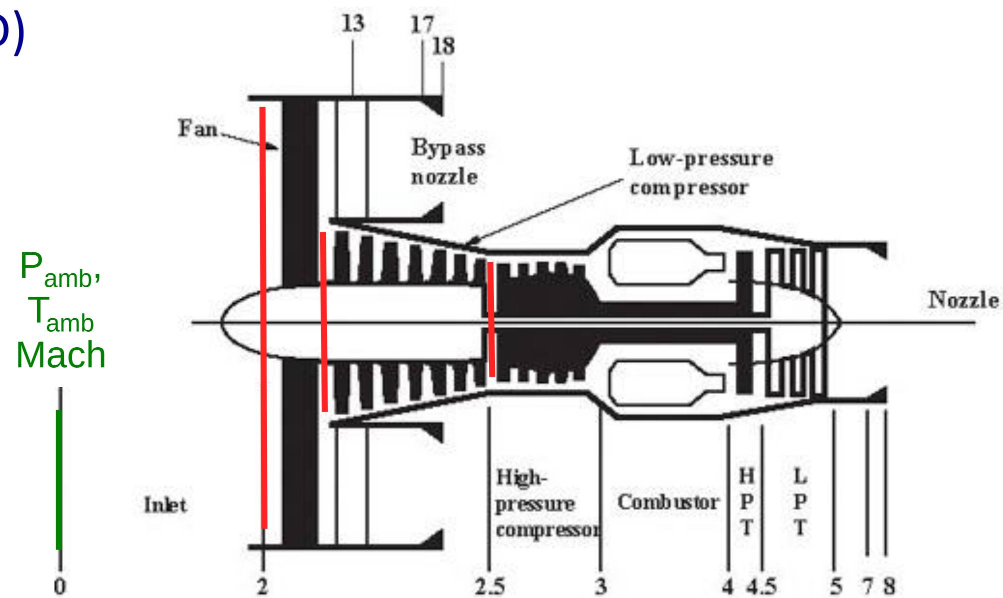
Provide the static conditions (Ps, Ts, Mach) at the inlet plane of either

- Engine (fan face conditions)
- Driven Rig (LPC inlet, etc)

Define target cloud (TWC, MVD)

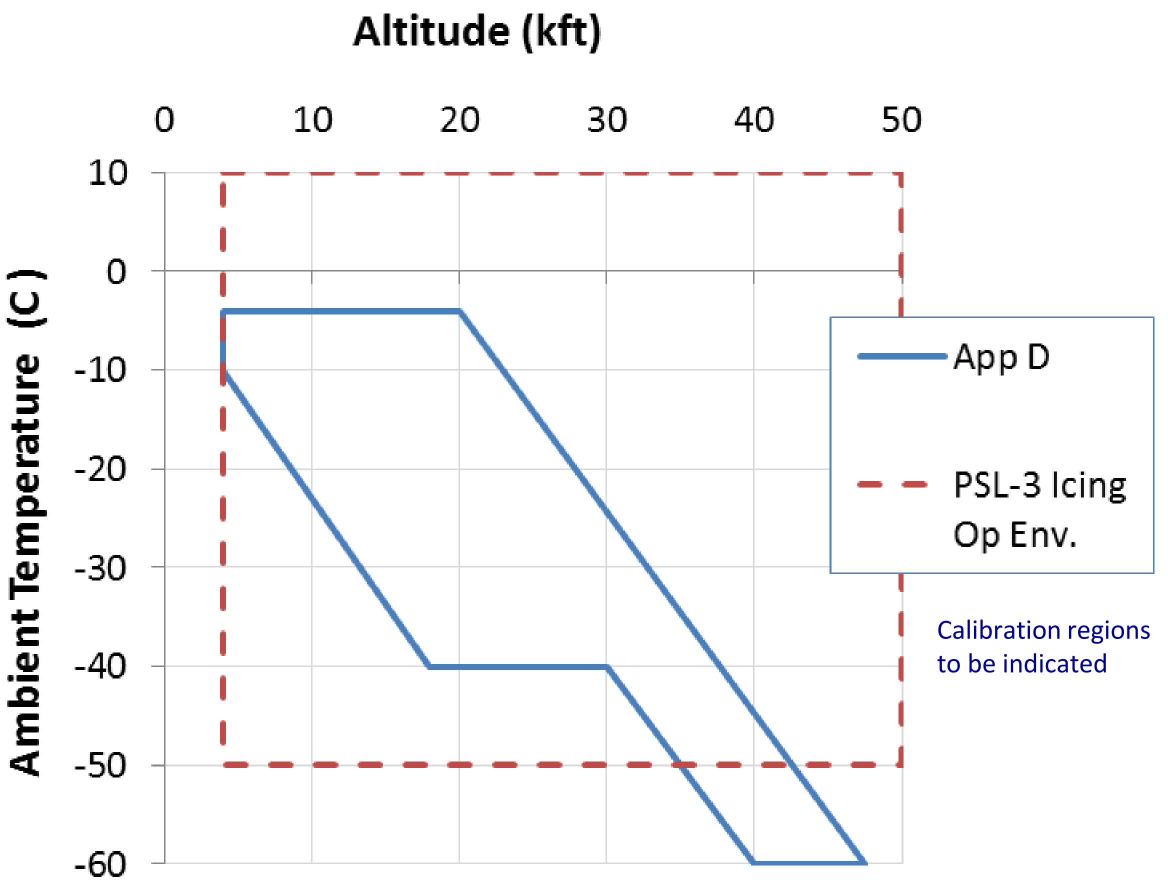
- Appendix D/P
- Appendix C
- Large Drop

Conduct calibration toward request to see what PSL can cover.



(from Aircraft Engine Design, Mattingly)

PSL-3 Envelope



Calibration regions to be indicated

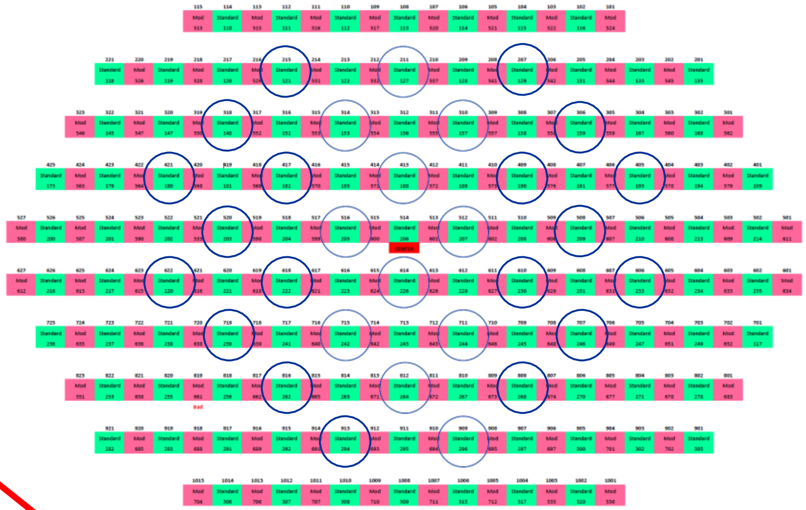
PSL Icing Cloud Hardware

Spray Bars – Cloud Generation

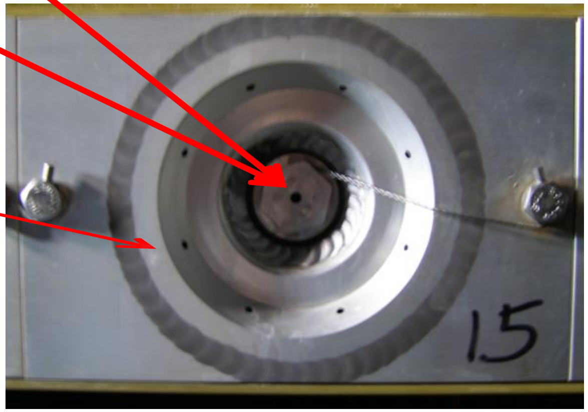
- Ten Spray Bars; total of 110 **Standard**
  - nozzles and 112 **Mod1** nozzles.

- Each nozzle is individually controlled.

- Nozzle controls:
  - **Pair**, atomizing air pressure: 5 – 90 psid, Tair temperature: 45 – 180 F.
  - **Pwat**, water pressure: 10 – 300 psid, Twat temperature: 45 – 180 F.
  - **DeltaP** = DP = (Pwat – Pair)
  - SBCA, Spraybar cooling air. P: 5 – 40 psid, T : -40 – 40 F.



Full (every) or Half (every other) Pattern



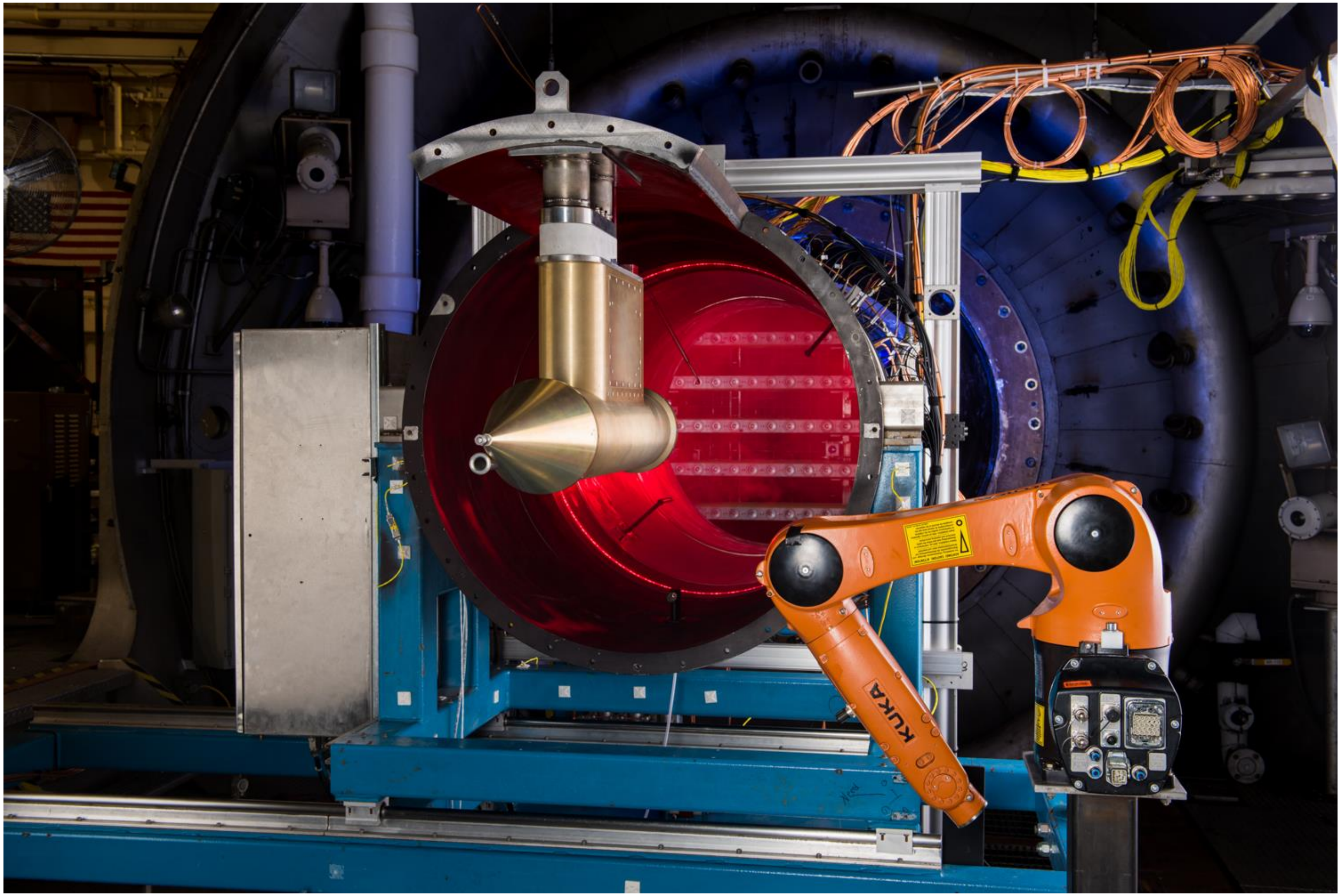
(Pair, DeltaP) => (MVD, TWC)

At a given air mass flow rate

Water Content Instruments – IKP

Iso-Kinetic Probe

SEA Inc.



Ice Catch Tube system not completed for the May 2015 Entry.

Water Content Instruments – Hot wire

Multi-Wire (TWC & LWC)

(MW)

2-mm reverse half-pipe (083)
2-mm half-pipe (TWC)
0.5-mm wire (021)
*Collection Efficiency Corrected**

Robust Probe (TWC only) SEA Inc.

(RP)

ribbed (rRP)

3.8-mm half-pipe
No collection efficiency correction, yet.

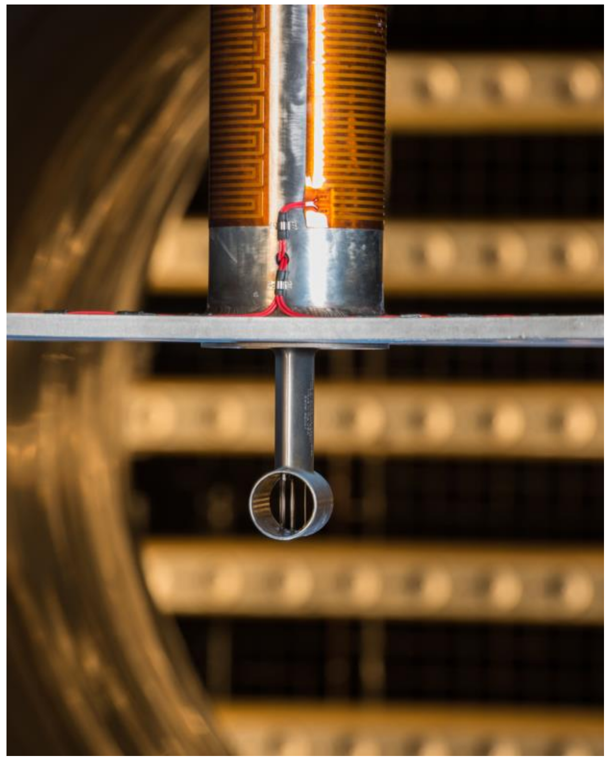
*Ref: Rigby, Struk, Bidwell, "Simulation of fluid flow and collection efficiency for an SEA multi-element probe", AIAA 2014-2752

Water Content – Installation and Analysis

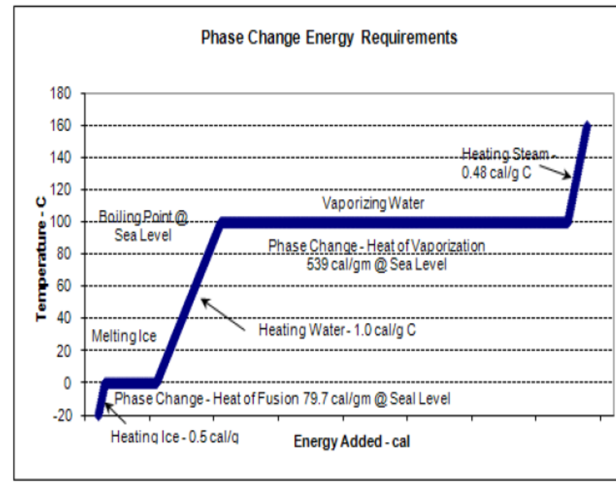
Splitter Plate

Bullet nose
(not recommended)

2012



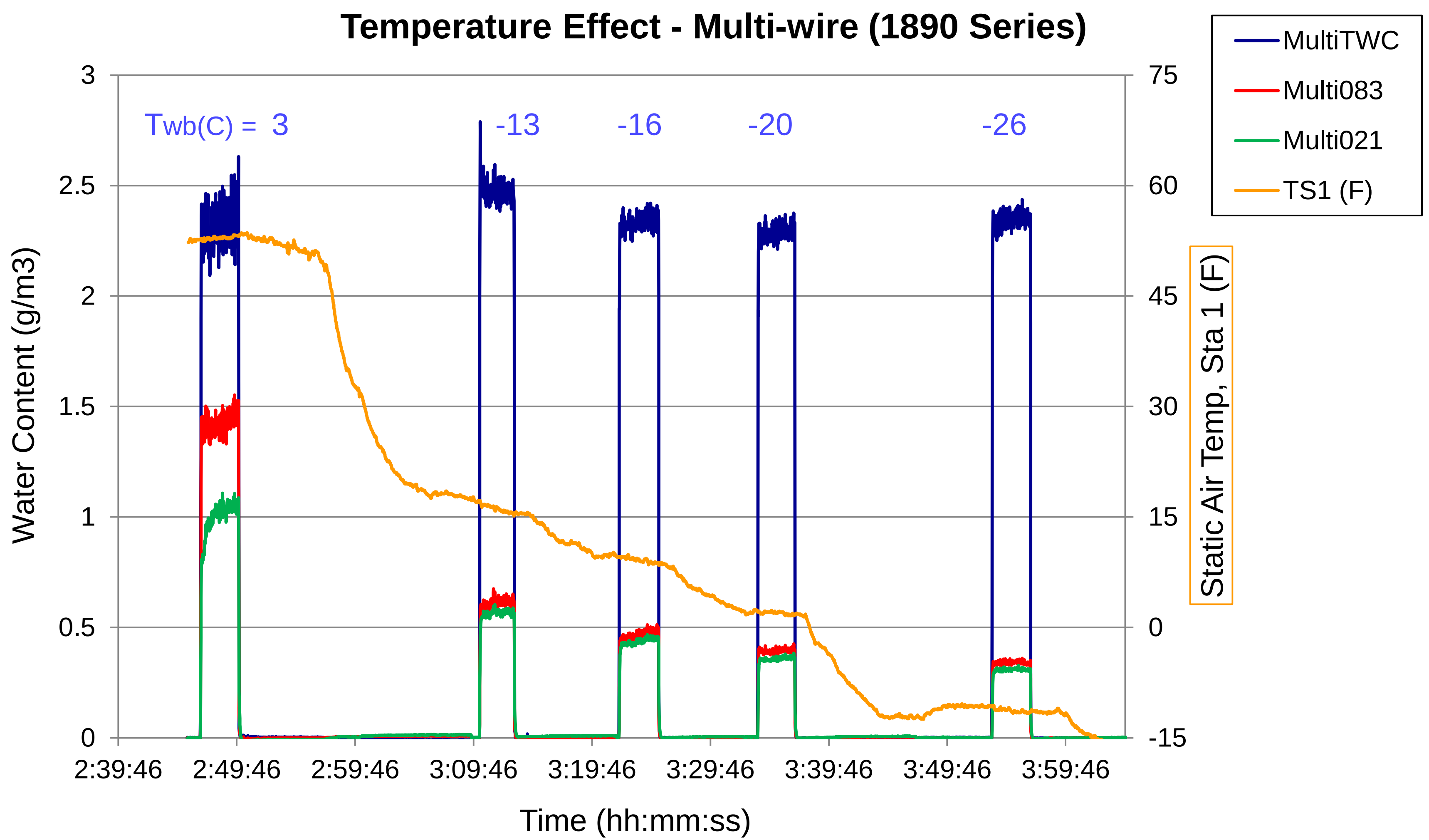
2014 & 2015



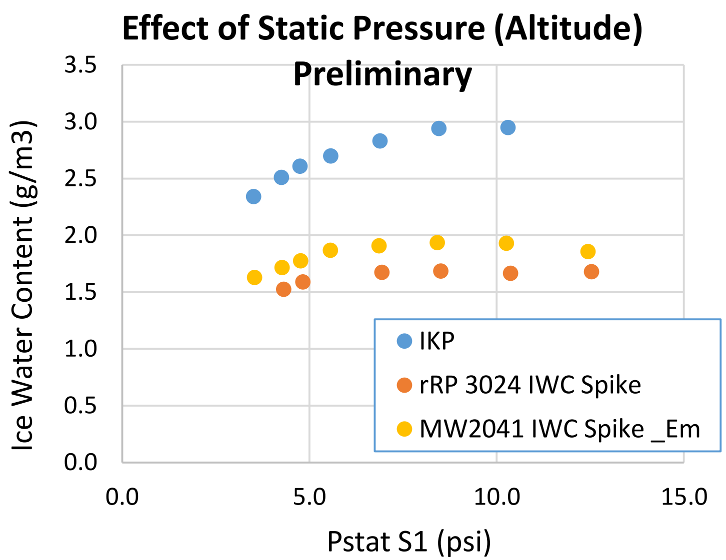
SEA WCM-2000 User Manual

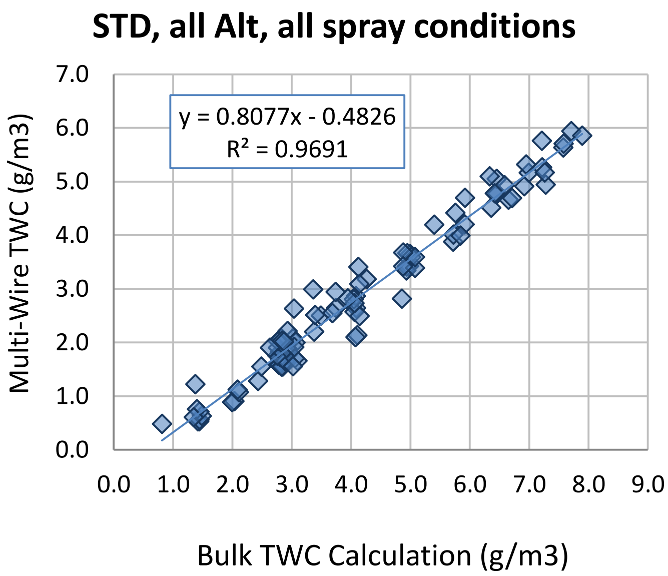
$$IWC\left(\frac{g}{m^3}\right) = \frac{C * P_{sense,wet}}{\left[L_{evap} + C_{liq}\left(T_{evap} - T_{amb}\right) + \underbrace{L_{fus} + C_{ice}\left(T_0 - T_{amb}\right)}\right] * V * L_{sense} * W_{sense}}$$

MW Response to Temp. change at Altitude (25 um)



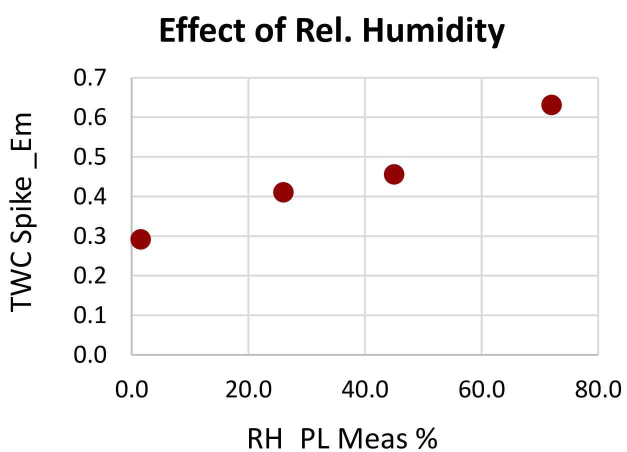
Sample TWC Measurements





Config1: Effects of

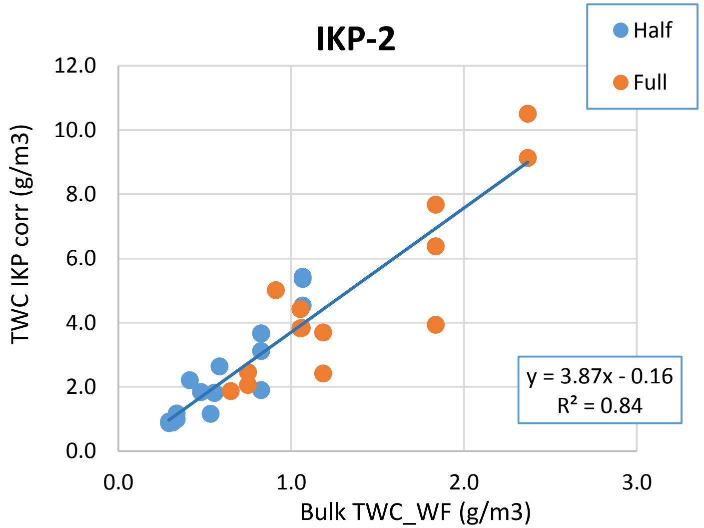
- Altitude
- Relative Humidity

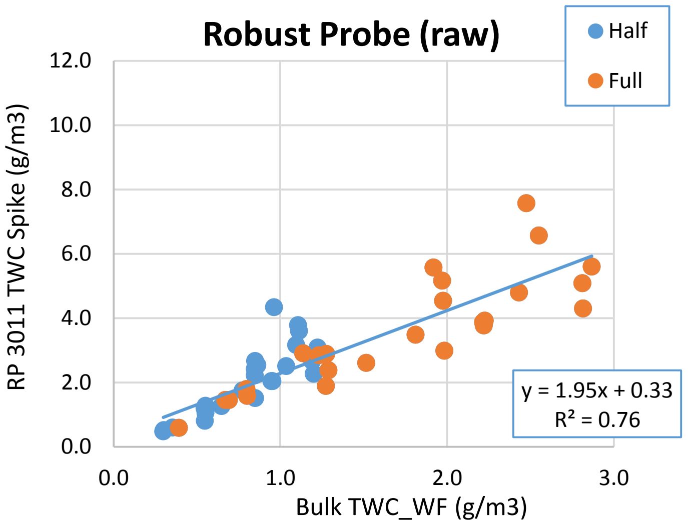


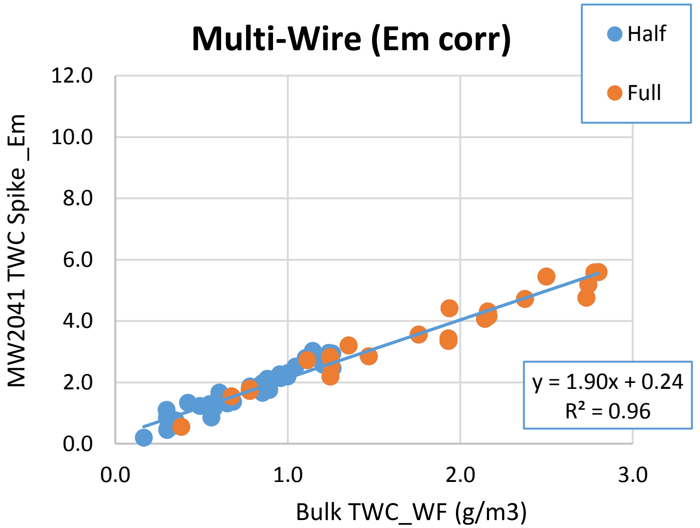
Config 2: Correlation between Measured and Calculated

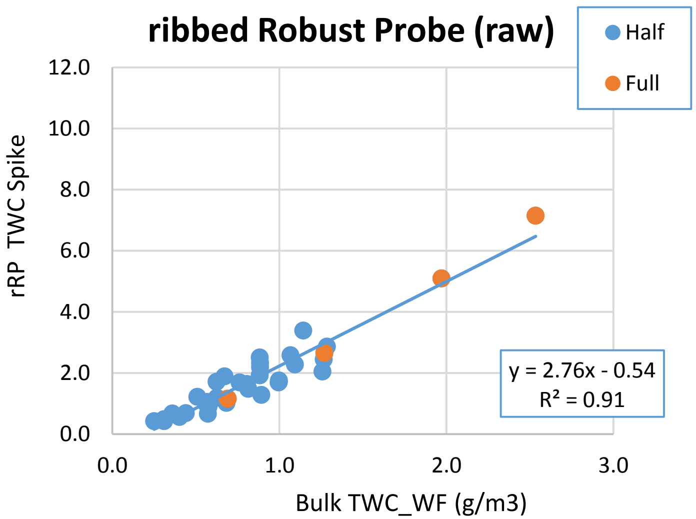
$$\text{Bulk TWC} = \frac{\text{mass\_water / time}}{\text{mass\_air / time}}$$

Water Content Sensor Comparison



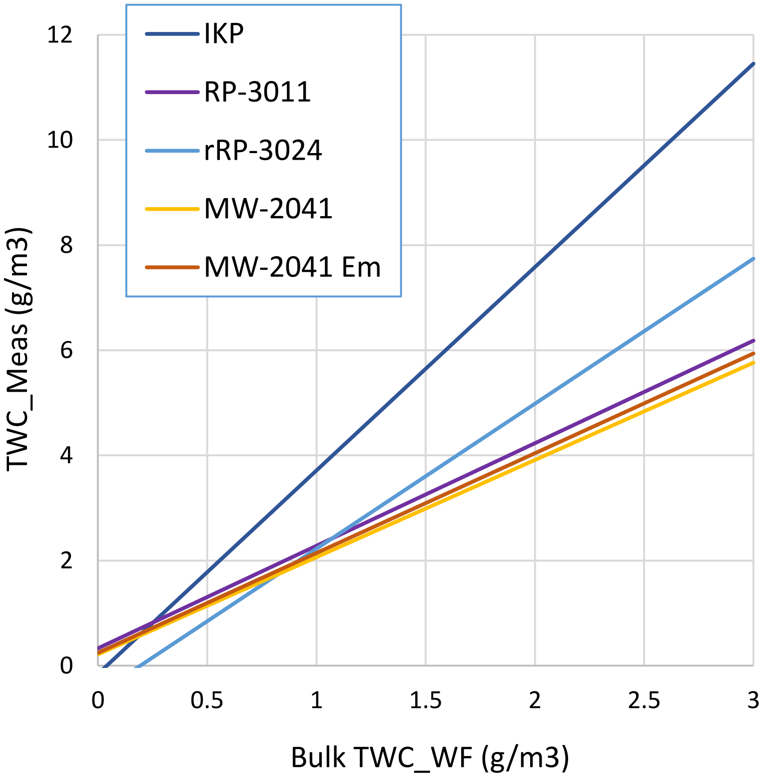




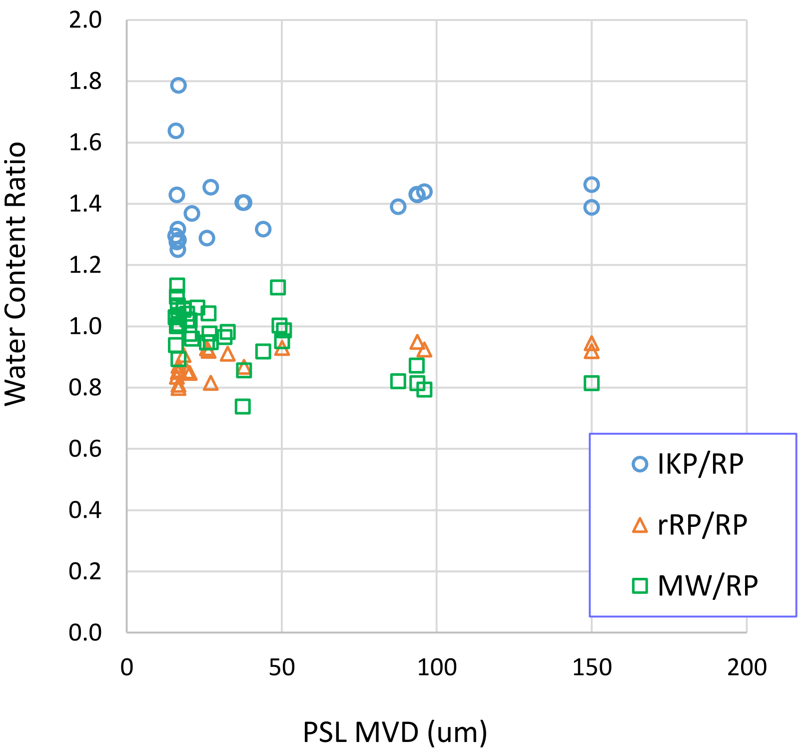


Water Content Sensor Comparison

Sensor Fit Comparison



Sensor/RP v MVD



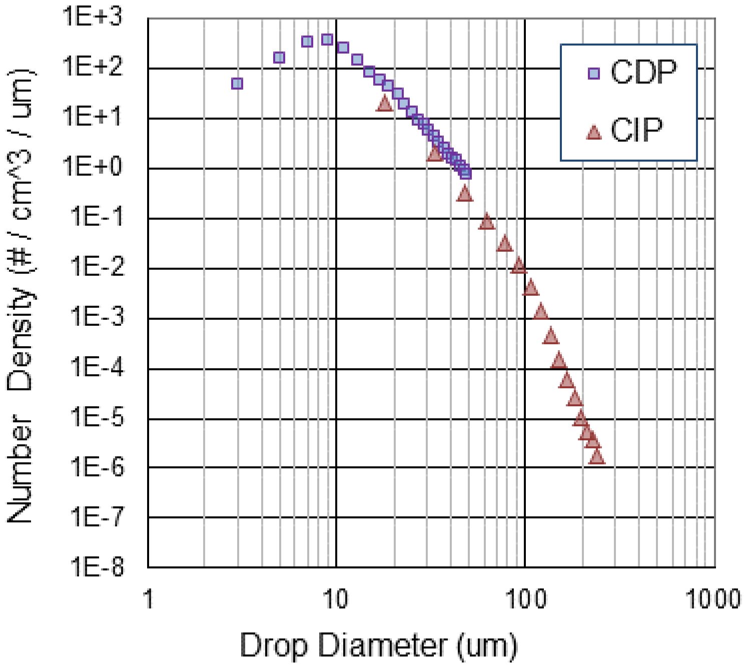
Drop Sizing Instruments

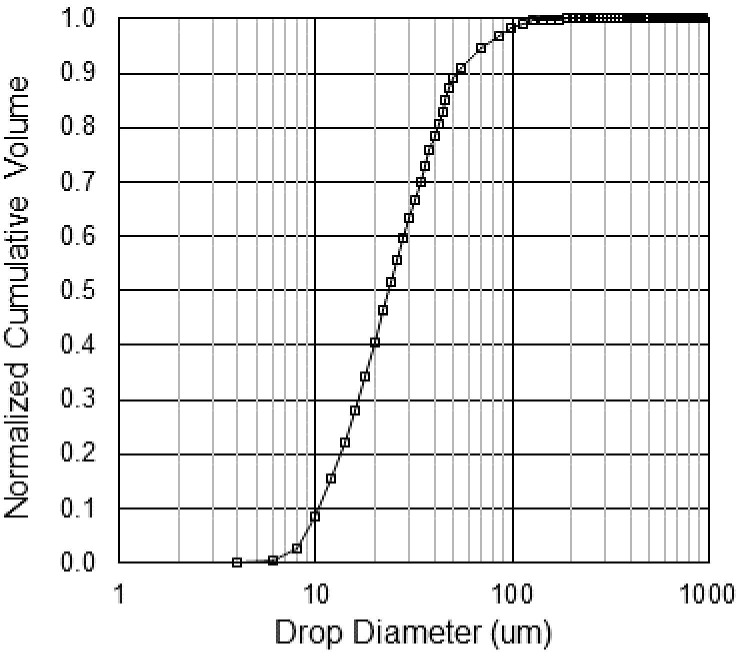
DMT Inc.

CDP (2 – 50 um)
Forward Scattering

CIP-GS (15 – 930 um)
Shadowing

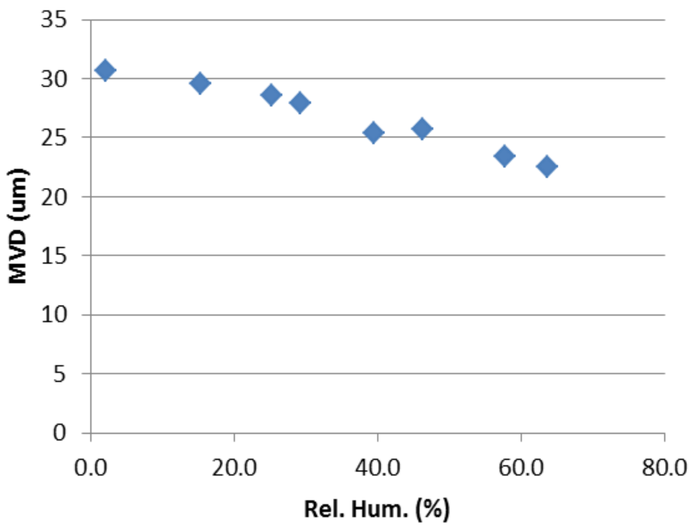
Sample Combined Distributions



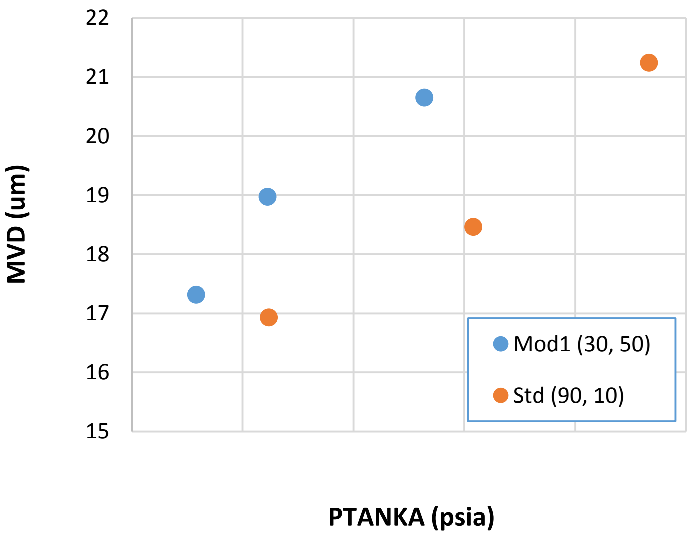


Sample MVD Results

Effect of
Relative Humidity

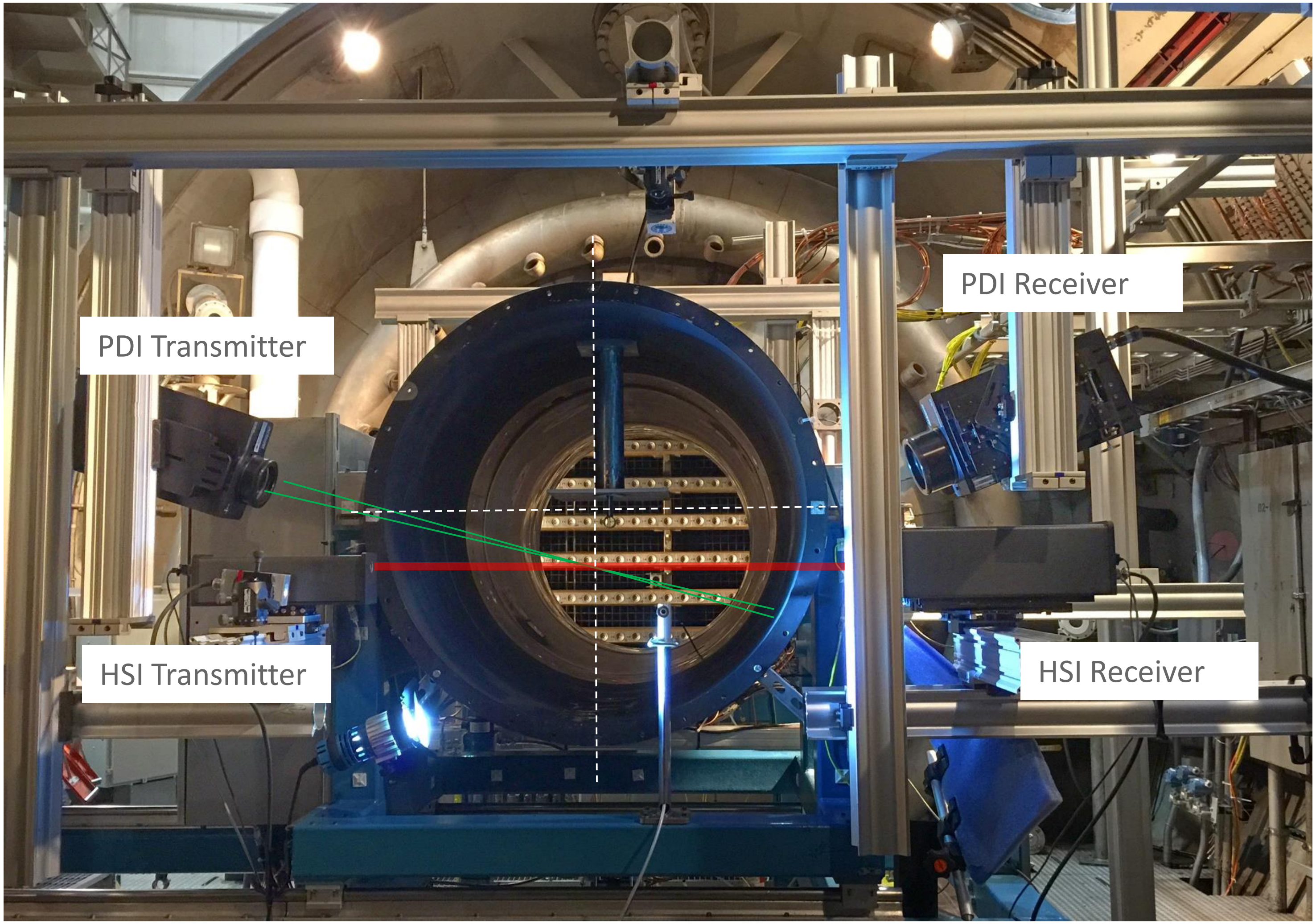


Effect of Altitude
(Tank Pressure)



Additional Particle Sizing Techniques

Artium, Inc.



Phase Doppler Interferometer

- Particle size
- Particle velocity
- LWC
- Number density

High Speed Imaging

- Particle size (ice & liquid)
- Shape
- LWC
- Number density

Cloud Uniformity Diagnostics

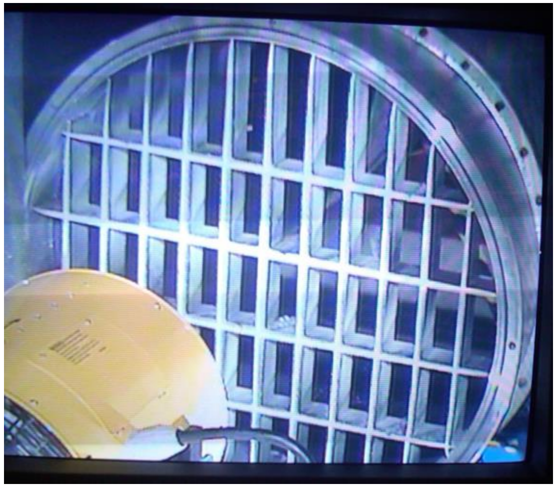
- Grid
    - Supercooled liquid only
    - Low speed only
- Laser Sheet *
- Tomography *

Uniformity is required for Bulk TWC calculation.

* Bencic, T., et. al, “Advanced Optical Diagnostics for Ice Crystal Cloud Measurements in the NASA Glenn Propulsion Systems Laboratory”, AIAA 2013-2678, 2013.

Cloud Uniformity Measurements

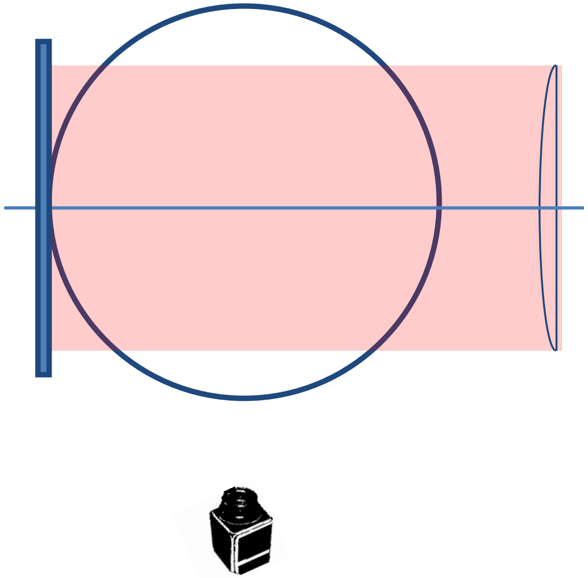
Uniformity Grid 3x6 in



Liquid Water Only
Limited Speed, Time

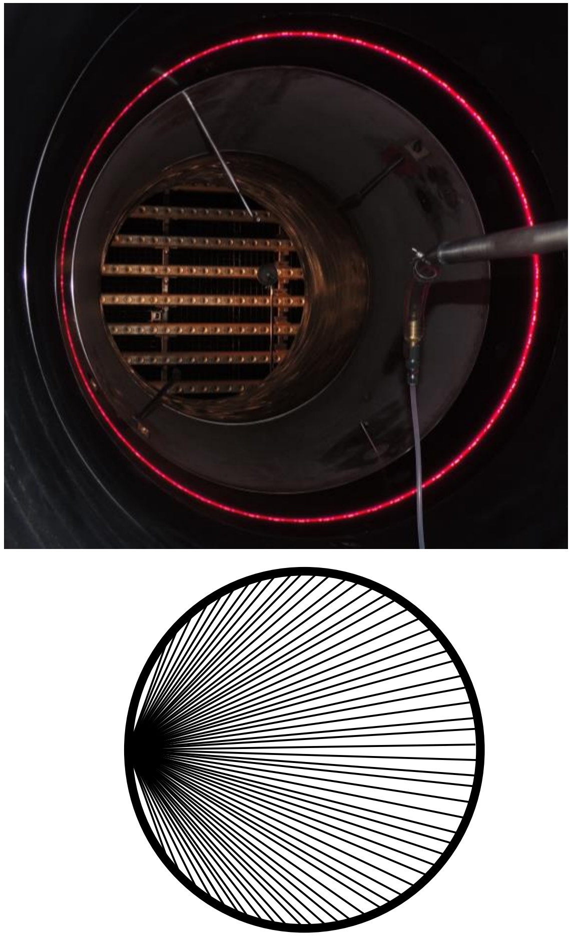
Long time spray for visualization only.

Laser Sheet @ duct exit



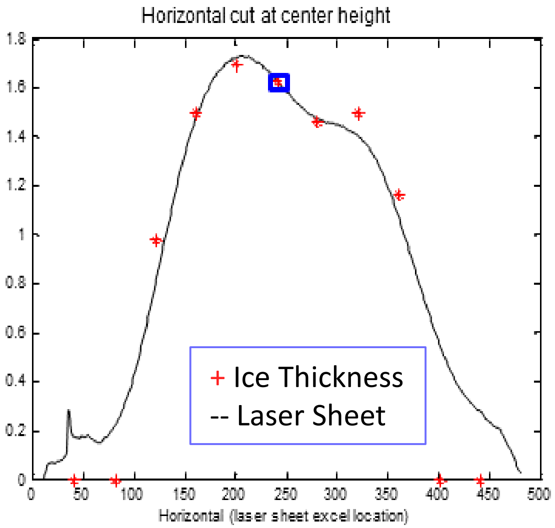
Light Extinction Measurements

Tomography in duct

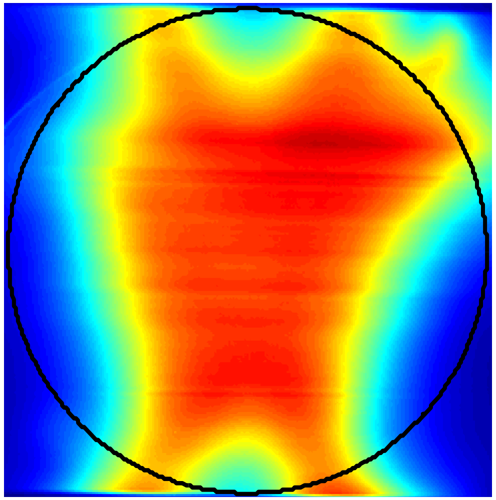


Cloud Uniformity Results

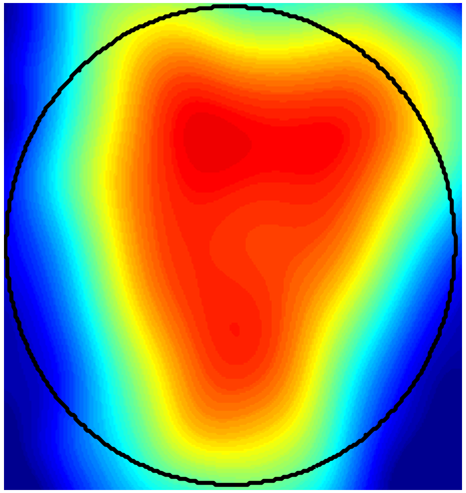
Grid & Laser Sheet

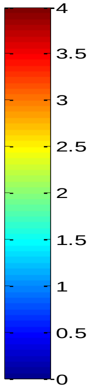


Laser Sheet @ duct exit



Tomography in duct





TWC (g/m3)

	TWC_RP (g/m^3)	Bulk TWC (g/m^3)	Max TWC (g/m^3)	Bulk / RP ratio (%)
Laser Sheet	3.30	2.44	3.74	74.1
Tomography	3.30	2.44	3.58	74.0

Particle Temperature

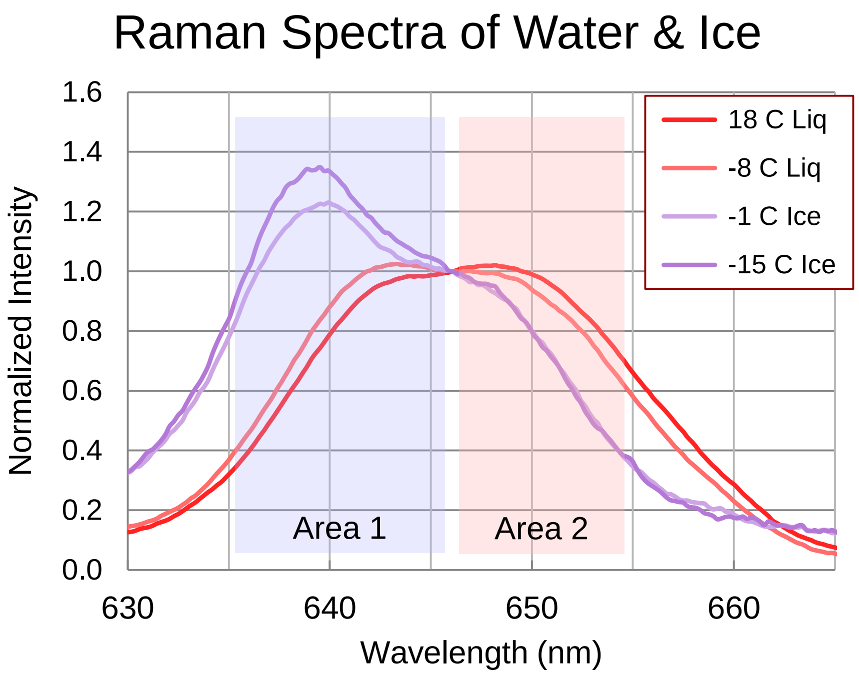
Raman Scattering – Primer

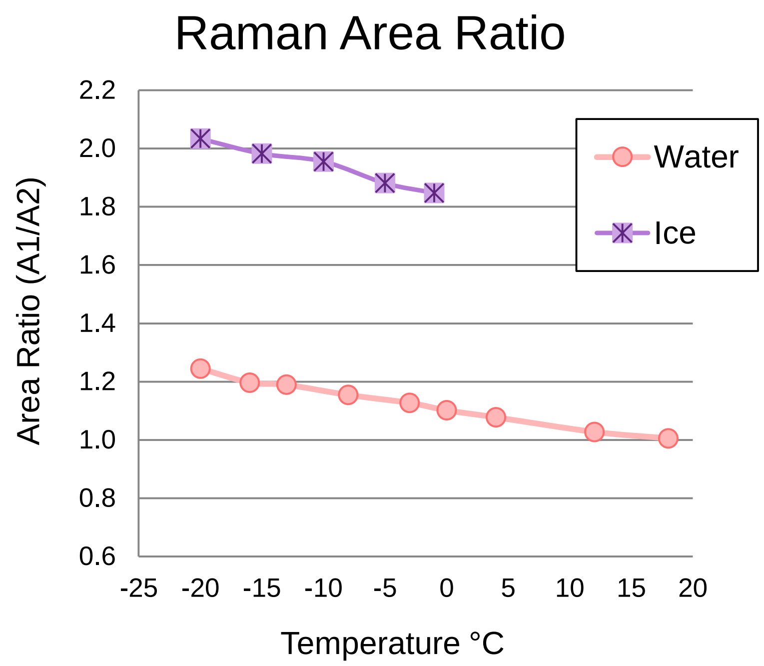
- Measures surface temperature
- Measures average bulk particle phase – ice or water
- Is a very low light technique, signal can be contaminated by light from other techniques or cell lights

Adding a fluorescent dye greatly helps with signal gain.

Raman Scattering – Particle Phase & Temp.

T. Bencic's bench top results





Future Tasks

- Continue analysis of May 2015 cloud characterization data
- Implement calibration curves
- Evaluate MVD sensitivity to configuration changes.
- Publish report

With thanks to the PSL Cloud Cal Team:

- **Bryan Rosine**
- **Jonathan Borman**

Questions?